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Fact Sheet for the Chairman, Committee on the Budget, U.S. Senate

February 1991

FEDERAL RESEARCH

Super Collider Estimates and Germany's Industrially Produced Magnets

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GAO

United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

B-242744

February 12, 1991

The Honorable Jim Sasser
Chairman, Committee on the Budget
United States Senate

Dear Mr. Chairman:

In response to your December 4, 1990, request, we obtained information on the growth of the Department of Energy's (DOE) cost estimate for its Superconducting Super Collider (SSC) and on Germany's experience with industrially produced superconducting magnets for its Hadron Electron Ring Accelerator (HERA). With respect to the SSC, you asked for a chronological history of the SSC cost estimates from initial research and development to the current cost estimate. You were further interested in ascertaining whether Germany's experience indicates that industry could successfully produce superconducting magnets for a high energy physics facility. We are also providing information on the SSC approach to developing and producing superconducting magnets. This information is being provided for information only and is not intended as a judgment about the appropriateness of either approach.

HERA, located at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany, is a high energy physics facility that will collide protons with electrons in a 3.9-mile ring. The SSC, currently estimated to cost $8.2 billion, will be a high energy physics facility located about 25 miles south of Dallas, Texas. It is substantially larger and more powerful than HERA and will collide two high energy beams of protons in a 54-mile oval underground ring. Both HERA and the SSC will use superconducting magnets to bend and focus protons as they circulate through the ring.[1] HERA is the first accelerator to use superconducting magnets produced by industry.

[1]HERA uses conventional magnets for its electron beam and superconducting magnets for its proton beam.

In summary, we found:

Since the SSC was conceived, DOE has presented many cost estimates for the project. These cost estimates are not necessarily comparable because some estimates did not include all project costs and/or did not have the same time frame. For example, in 1984, the first estimate was for about $4 billion in constant 1990 dollars, but did not include all project costs, such as site acquisition and continuing research and development on accelerator components.[2] The 1986 estimate of about $5 billion in constant 1990 dollars was the first to represent the total project costs. By 1989, DOE estimated that the total project cost was $5.1 billion in constant 1990 dollars. Various DOE groups have estimated the SSC to cost between $8.4 billion and $11.8 billion in current dollars.[3] DOE's Office of Energy Research reconciled the various estimates, and on the basis of that reconciliation the Deputy Secretary of Energy announced in early November 1990 that the SSC's total project cost is $8.2 billion in current dollars. The chronology is presented in section 1.

DESY's experience with HERA shows that superconducting magnets can be industrially produced. Although numerous minor problems were encountered during the development and production of the magnets, DESY officials told us that such problems should be expected when new technologies are involved and that these problems were resolved. Amendments to DESY's contract with the firm producing magnets in Germany increased cost by less than 7 percent (from about $29.5 million to about $31.5 million) over the 3-year life of the contract, and the magnets were delivered as scheduled. DESY officials attributed their success in having industry produce superconducting magnets to their

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[2]Estimates in constant dollars adjust for the estimated effects of inflation on funds to be spent in future years.

[3]Cost estimates in current dollars are estimates of total costs as incurred in the year of expenditure. Thus, they are not comparable to the dollar figures adjusted to constant 1990 dollars. We did not adjust DOE's November 1990 estimate to constant dollars because DOE has not published the information necessary to do so.

-- having one person at DESY with the authority and the knowledge needed for making all decisions concerning the technology, budget, and schedule for the magnets;

-- clearly identifying the specifications for the industrially produced magnets before going out for bids;

-- retaining the flexibility to negotiate with the contractor by maintaining ownership over the tooling and the technology; and

-- fully measuring and testing each magnet before accepting and installing it into the accelerator ring.

The SSC Laboratory is responsible for designing, building, and operating the SSC. In regard to the factors DESY officials mentioned, the SSC Laboratory

-- relies primarily on other DOE laboratories' technical expertise with superconducting magnets,

-- went out to industry for bids before building or testing a prototype magnet of the current design,

-- is using an approach that allows one contractor to take the lead in the design and development of tooling and techniques for producing magnets, and

-- plans to rely on the contractor to measure and test the magnets at room temperature and on itself to test about 19 percent of the magnets at operating temperature (-269 degrees centigrade) before installing them in the accelerator ring.

Additional information on DESY's experience and DESY officials' comments on producing superconducting magnets are presented in section 2.

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Our objective was to develop a chronological history of the SSC cost estimates and to provide information on DESY's experience with industrially produced superconducting magnets. To develop the chronology of the SSC cost estimates, we reviewed existing DOE program literature on the SSC and congressional hearings related to project funding. We also examined the results of various internal DOE analyses and outside reviews of the SSC cost estimates. We noted that some DOE cost estimates were not comparable

because they were in different constant fiscal year dollars or were in current dollars. We converted constant 1984, 1986, and 1988 fiscal year dollars to constant 1990 dollars and converted current fiscal year dollars into constant year dollars where the information was available to do so. We did not independently verify the information obtained.

To obtain information on DESY's experience with superconducting magnets, we interviewed the DESY officials responsible for the HERA project and for the superconducting magnets in particular, and we reviewed documents they provided on the HERA project. To place this information in perspective, we examined DOE and SSC Laboratory documents related to the key factors cited by DESY officials. To provide you with the information in time for your consideration of DOE's budget request, we did not independently verify the information they provided.

We discussed the information presented in this fact sheet concerning the HERA magnets with DESY officials and matters concerning the SSC with DOE officials. These officials agreed with the accuracy of the facts presented. As requested, we did not obtain official agency comments. Our work was conducted in December 1990 and January 1991. The review was performed in accordance with generally accepted government auditing standards.

As arranged with your office, unless you publicly announce its contents earlier, we plan no further distribution of this fact sheet until 10 days from the date of this letter. At that time we will send copies of this fact sheet to the appropriate House and Senate committees, the Secretary of Energy, and the Director, Office of Management and Budget. Copies will also be made available to other interested parties on request.

Should you have questions or need additional information, please contact me on (202) 275-1441. Major contributors to this fact sheet are listed in appendix I.

Sincerely,

Victor S. Rezendes
Director, Energy Issues

<u>CONTENTS</u>

<u>ABBREVIATIONS</u>

CDG	Central Design Group
DESY	Deutsches Elektronen-Synchrotron
DOE	Department of Energy
GeV	billion electron volts
HEPAP	High Energy Physics Advisory Panel
HERA	Hadron Electron Ring Accelerator
ICE	Independent Cost Estimating
OER	Office of Energy Research
SSC	Superconducting Super Collider
R&D	research and development
RDS	Reference Designs Study
TeV	trillion electron volts

SECTION 1

CHRONOLOGICAL HISTORY OF THE SSC COST ESTIMATE

BACKGROUND

The Superconducting Super Collider (SSC) is a proton-proton collider with an energy of 20 trillion electron volts (TeV) in each of its two beams. Its principal feature is two rings of superconducting magnets located in an underground tunnel 54 miles in circumference. The two rings of magnets will steer and focus the proton beams in opposite directions until they collide at various interaction regions where large detectors record the events for analysis by physicists. DOE's current cost estimate for the SSC is $8.2 billion in current dollars.[1]

This chronology traces SSC cost estimates from those based on earlier feasibility and conceptual development efforts to those based on the final site-specific design study. We also included excerpts from congressional committee hearings regarding the validity of proposed estimates and resulting cost growth. In addition, we have included the results of various internal DOE analyses and outside reviews of SSC cost estimates.

In this chronology the SSC cost estimates are presented in the constant fiscal year dollars as they were presented by DOE.[2] In addition, we have converted these estimates to constant 1990 dollars for comparability. The most recent cost estimates are presented in current dollars only because DOE has not yet published the information necessary to convert the estimate into constant 1990 dollars.[3]

CHRONOLOGY OF THE SSC COST ESTIMATES

1983 DOE started preliminary research and development (R&D) for the SSC in 1983. On November 19, the House Committee on Science and Technology held hearings on the future direction of DOE's high energy physics program and specifically of the SSC. In December, DOE began a

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[1]Cost estimates in current dollars are estimates of the total costs as incurred in the year of expenditure.

[2]Estimates in constant dollars adjust for the estimated effects of inflation on funds to be spent in future years.

[3]When dollar figures are reported in current terms, they are not comparable to the dollar figures adjusted to constant 1990 dollar terms.

Reference Designs Study (RDS) to examine magnet and systems design options, perform technical feasibility studies, and make the first cost estimates of the SSC.

1984 The RDS, completed in April, concluded that the SSC would be technically feasible using existing technology and engineering. The RDS estimated that SSC construction would cost about $3 billion in constant fiscal year 1984 dollars or about $4 billion in constant 1990 dollars. This estimate did not include costs for (1) continuing R&D on accelerator components, (2) site acquisition, (3) the pre-operational commissioning of the facility, (4) procurement of central computers, and (5) fabrication of an initial complement of detectors.[4]

In May, a DOE committee reviewed the RDS and found the construction cost estimates to be credible. However, the committee recommended increasing the RDS cost estimates by about $200 million to include important but modest additions to the scope of the project and to bring the engineering and administrative cost estimates into closer agreement with recent high energy physics experience. On the basis of cost-sensitivity calculations and the committee's collective judgment, the committee estimated that the construction cost of the SSC would be no more than 1.25 times the highest RDS estimate, or about $3.75 billion in constant fiscal year 1984 dollars ($4.58 billion in constant 1990 dollars).

DOE designated Universities Research Association, a consortium of 72 U.S. and Canadian research universities, to conduct SSC research, development, and design activities. The Association formed the SSC Central Design Group (CDG) hosted by DOE's Lawrence Berkeley Laboratory in California.

1985 The major objectives for 1985 were to prepare the Superconducting Super Collider Parameters Document and to do R&D to select magnets. Five basic types of magnets were studied by teams at DOE laboratories, including Brookhaven National Laboratory in New York, Fermi National Accelerator Laboratory (Fermilab) in Illinois, and Lawrence Berkeley Laboratory; and at the Texas Accelerator Center. In August SSC magnets were selected, and construction and testing of prototype magnets began.

1986 The SSC Conceptual Design Report, published in March by the CDG, included a detailed cost estimate and schedule

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[4]Detectors are used by physicists to analyze the results of the beam collisions.

for SSC construction. The report estimated that the construction of the SSC facility would cost $3.01 billion in constant fiscal year 1986 dollars, or $3.48 billion in constant 1990 dollars, with a schedule duration of 6-1/2 years. In a separate report, the CDG documented a range of costs for the initial complement of detectors from $629 to $936 million. The cost estimate of about $4 billion in constant fiscal year 1986 dollars, or about $5 billion constant in 1990 dollars, included all R&D and pre-operation costs and the initial complement of detectors and computers.

In May, DOE's Office of Energy Research (OER) published the Report of the DOE Review Committee on the Conceptual Design of the SSC. OER's review concluded that the cost estimate of $3.01 billion for the construction project was credible and consistent with the scope of the project and that the proposed 6-1/2 year schedule for constructing the project appeared feasible for the assumed funding profile.

DOE's Independent Cost Estimating (ICE) staff also reviewed the Conceptual Design Report and related costs. They suggested increasing the CDG construction cost estimate of $3.01 billion by $428 million in constant fiscal year 1986 dollars, or $494 million in constant 1990 dollars, and the costs for detectors and computers by $506 million in constant fiscal year 1986 dollars, or $584 million in constant 1990 dollars.

According to a DOE official, DOE held meetings to reconcile differences between the ICE and CDG reports. The cost differences were not reconciled, but the ICE group agreed that DOE should proceed with the project and that the cost estimate should be further updated after the final site had been selected.

1987 DOE presented the Congress with a total project cost estimate for the SSC of $4.4 billion in constant fiscal year 1988 dollars ($4.8 billion in constant 1990 dollars) or $5.3 billion in current dollars. This estimate included the costs of construction, R&D, detectors, computers, and pre-operations.

For fiscal year 1988, DOE requested $10 million for construction-related activities and $25 million for R&D related to the SSC.

According to the March 4 House Congressional Record, Representative Tim Valentine of North Carolina questioned the validity of the $4.4 billion cost estimate.

In April, the Director of OER testified before the House Committee on Science, Space, and Technology. He expressed confidence in the SSC project's feasibility and schedule and in the accuracy of cost estimates. He further stated that the proposed SSC "may be the best analyzed physics project ever brought forward by the administration to Congress." He further attributed the quality of the SSC analysis not only to the extensive amount of work involved in developing the SSC's conceptual design, but also to experience gained from the terminated Isabelle project.[5] He added that obtained experiences required DOE to improve planning for future physics projects.

The Director indicated in the congressional hearing that the cost estimate of $4.4 billion in constant fiscal year 1988 dollars (or $4.8 billion in constant 1990 dollars) was accurate to within 10 percent and that the site would have to be selected before the estimate could be improved.

1988 During a congressional hearing in March before the Committee on Science, Space, and Technology, the Under Secretary of DOE stated that the total project cost of the SSC was estimated to be $4.4 billion in constant fiscal year 1988 dollars (or $4.8 billion in constant 1990 dollars). This estimate included the costs of construction, R&D, detectors, computers, and pre-operations. He stated that in current dollars the total project cost was $5.3 billion, with a target completion date of 1996.

In its fiscal year 1989 budget request for the SSC, DOE requested an increase in R&D funding from $25 million in fiscal year 1988 to $64 million. DOE also requested $283 million to begin construction.

In October the Congressional Budget Office published a report entitled <u>Risks and Benefits of Building the SSC</u>. This report states that DOE's estimate of detector costs may be understated by $200 million to $500 million and that superconducting magnet costs could increase by $270 million. In response to the report, DOE stated that the SSC can be undertaken with confidence in the cost estimate of $4.4 billion in constant fiscal year 1988 dollars (or $4.8 billion in constant 1990 dollars).

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[5]The Isabelle project was an earlier DOE accelerator project located at Brookhaven National Laboratory. After several years, the project was terminated by DOE in 1983 because of various problems, including design difficulties and delays in fabricating the magnets.

1989 The Congress did not appropriate construction funds for the SSC in the fiscal year 1989 budget. Consequently, site preparation did not begin in January 1989 and operations originally scheduled to begin in 1996 were delayed until at least 1998. According to DOE's budget request, the estimated cost of the SSC was $5.9 billion in current dollars (or $5.1 billion in constant 1990 dollars).

In January, DOE chose Universities Research Association to serve as the management and operating contractor for the SSC with responsibility to design, build, and operate the SSC Laboratory in Texas. In its first year, the SSC Laboratory prepared a site-specific design and associated schedules and cost estimates for the SSC.

According to its Director, the SSC Laboratory began its work on the design of the SSC in early 1989, using the 1986 conceptual design as a starting point. He stated that the experience of the intervening 3 years (since the 1986 Conceptual Design Report) had yielded considerable new information for the designers. He also stated that operating experience at other accelerators had provided information about the behavior of particles in accelerators and the performance of superconducting magnets, which led the SSC Laboratory to propose design changes to the 1986 conceptual design. Changes included (1) increasing the injection energy into the collider from 1 TeV to 2 TeV, (2) increasing the inner diameter of the magnet coil (aperture) from 40 millimeters to 50 millimeters, and (3) increasing the circumference of the collider ring by about 1 mile.

1990 Recognizing that the proposed design changes would result in increased costs, the Acting Director of DOE's Office of Energy Research asked the SSC Laboratory to consider reducing the size and energy level of the project. However, a High Energy Physics Advisory Panel (HEPAP) report indicated that reducing the energy would risk losing important physics. The panel fully endorsed the design as well as the proposed technical design changes responsible for increasing the cost estimate.

In March, the Secretary of Energy said DOE had decided to accept the SSC Laboratory's recommendation to increase the injection energy from 1 TeV to 2 TeV and to increase the magnet aperture from 40 millimeters to 50 millimeters. DOE officials presented the design changes at congressional hearings before the Subcommittee on Energy and Water Development, House Committee on Appropriations, and the Subcommittee on Energy Research and Development, Senate Committee on Energy and Natural Resources. The officials said that the SSC cost would be greater than the earlier estimate of $5.9 billion in current dollars (or $5.1

billion in constant 1990 dollars), possibly by as much as $1 billion to $2 billion. The SSC Laboratory Director, testifying before the Senate Committee on Energy and Natural Resources, maintained that the higher amount did not constitute a cost overrun. He attributed the increase to necessary design changes and resulting revisions of earlier technical and economic assumptions. He concluded that the higher cost estimate was a conservative projection of the costs for completing the SSC.

In June, the SSC Laboratory completed the Site-Specific Conceptual Design Report and Cost Estimate, which included the baseline cost estimate. The SSC Laboratory estimate projected a total project cost of $7.8 billion in current dollars. This estimate did not include the $131 million expended in fiscal years 1988 and 1989. In July, the SSC Laboratory published the Site-Specific Conceptual Design, Executive Summary, which estimated project completion by the end of 1998.

After the SSC Laboratory refined its design and associated cost and schedule estimates, DOE conducted three independent reviews of the Laboratory's work. Two DOE reviews were completed by OER and ICE staff. At DOE's request, the third independent review was conducted by the HEPAP Subpanel on SSC Cost Estimate Oversight.

In its review, OER recommended the SSC Laboratory total project base cost estimate be increased by $57 million in constant 1990 dollars and the associated contingency allowance by $395 million constant 1990 dollars. The major element of the contingency increase was $290 million for the superconducting magnets. Translated to current dollars, OER's total project cost for the SSC is $8.4 billion.

In its review, DOE's ICE staff expressed the belief that the SSC Laboratory cost and schedule estimate for the SSC is both unrealistic and unachievable. ICE and SSC Laboratory estimates differ substantially for superconducting magnet costs, detector costs, contingency, escalation, pre-operations costs, prior years' costs, and anticipated costs due to schedule delays. The ICE total project cost estimate is $11.8 billion in current dollars.

In its review, the HEPAP subpanel recommended an increase in the SSC Laboratory's total project cost, including escalation and contingency, to $8.6 billion. Also, the subpanel recommended increasing the schedule by 6 to 12 months and adding $300 million to the detector budget.

After receiving the results of the reviews, the Office of the SSC in DOE's Office of Energy Research undertook a detailed reconciliation of the differences. On the basis of its assessment of all the data, the Office concluded that a total project cost of $8.2 billion in current dollars and completion by the end of fiscal year 1999 is the most appropriate cost and schedule baseline for the SSC.

In August, the SSC Laboratory published a revised <u>Cost Estimate Report</u>, which included a total SSC project cost estimate of $8.2 billion in current dollars. This estimate is the <u>Site Specific Conceptual Design Review Cost Estimate</u> with the agreed upon changes from the June 1990 reviews incorporated into it.

In early November, the Deputy Secretary of Energy announced the SSC cost estimate as $8.2 billion in current dollars.

SECTION 2

DESY'S EXPERIENCE AND COMMENTS ON PRODUCING SUPERCONDUCTING MAGNETS

BACKGROUND

The Deutsches Elektronen-Synchrotron (DESY), located in Hamburg, Germany, was founded in 1959 as a German national research center for particle physics. DESY's annual budget of about 230 million deutsche marks (about $153 million)[1] is financed by the federal government (90 percent) and the city-state of Hamburg (10 percent). More than 700 physicists from 84 universities and research institutes in 17 countries, including the United States, are involved in high energy physics experiments at DESY.[2] In April 1991, DESY plans to begin operating a new electron-proton collider, called the Hadron Electron Ring Accelerator (HERA). In HERA's 6.3-kilometer underground tunnel, protons accelerated in a storage ring to energies of 820 GeV (billion electron-volts) are to collide at specific interaction points with electrons accelerated to energies of 30 GeV. HERA is the first double storage ring collider for different types of particles. HERA is one of only two accelerators built to date that use superconducting magnets and is the only accelerator whose superconducting magnets have been industrially produced.[3]

In designing and constructing HERA, DESY made extensive use of existing accelerators to initially accelerate and inject the electrons and protons into the HERA storage rings. HERA is supplied pre-accelerated electrons and protons via two chains of three progressively higher energy injector accelerators. The last of these, an accelerator called PETRA II, which is a modification of a pre-existing accelerator called PETRA, injects electrons into the HERA ring at an energy of 14 GeV, and protons at an energy of 40 GeV. The injection energy levels for HERA were largely determined by the capability of the pre-existing DESY accelerators. For example, the 40 GeV injection energy level for protons was determined by the capability of the existing conventional magnets

[1]The January 18, 1991, New York exchange rate for the deutsche mark was 1.50 to $1.

[2]Physicists are generally provided free access to high energy physics accelerators throughout the world.

[3]An accelerator called the Tevatron, which began operating in 1985 at Fermi National Accelerator Laboratory (Fermilab), located in Batavia, Illinois, also uses superconducting magnets, which were produced at the laboratory.

in the PETRA accelerator to accelerate protons. See figure 1.1 for an aerial view of DESY, with the tunnels for the HERA and PETRA accelerators outlined.

Authorized in April 1984, HERA was completed after about 6-1/2 years of construction in November 1990. HERA was completed within 1 month of its original estimated schedule and within its original estimated cost of about 1.01 billion deutsche marks (about $673 million). About 72 percent of the costs were financed by the German federal government, 13 percent by the city-state of Hamburg, and 15 percent by various foreign governments, including the United States, in the form of components delivered to DESY.[4] Several other countries sent physicists, engineers, and technicians to Hamburg to provide assistance during HERA's construction.

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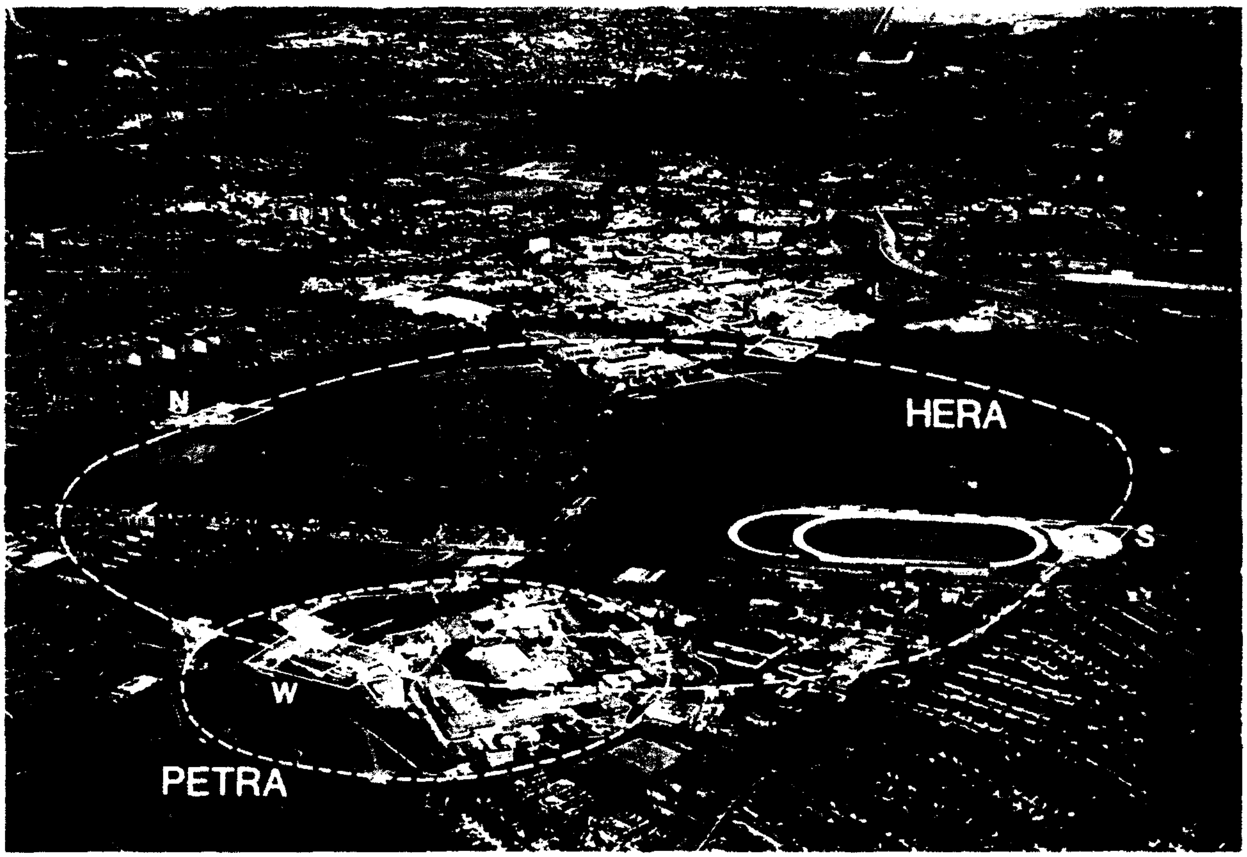
[4]Brookhaven National Laboratory, Upton, New York, performed quality control tests of all superconducting cable used in the superconducting magnets.

Figure 2.1: Aerial View of Deutsches Elektronen-Synchrotron

The German National Research Centre for Particle Physics DESY in Hamburg



(Release No: 611/87 LA HH)

The 6.3 km HERA tunnel runs predominantly under a large city park, under residential and industrial buildings, and under the DESY site with the 2.3 km pre-accelerator PETRA.

Source: DESY.

DESY EXPERIENCE WITH INDUSTRIALLY PRODUCED SUPERCONDUCTING MAGNETS

DESY's experience with HERA shows that superconducting magnets can be industrially produced. Although numerous minor problems were encountered during the development and production of the magnets, DESY officials told us that such problems should be expected when new technologies are involved and that these problems were resolved.

The HERA electron-proton collider at DESY is the first accelerator to use superconducting magnets produced by industry. DESY worked closely with a contractor, Asea-Brown-Boveri, in developing the basic design of the 9-meter-long HERA dipole magnet. When the basic design was finished in mid-1986, DESY and Asea-Brown-Boveri had built a total of five working prototype magnets at its plant in Mannheim, Germany. DESY then wrote detailed specifications and went out to industry for bids on a fixed-price contract for about half of the 453 superconducting dipole magnets (422 plus 31 spares). In September 1987, after receiving six to eight bids, DESY signed a fixed-price contract for 44.25 million deutsche marks (about $29.5 million) with Asea-Brown-Boveri, the company that had helped to develop the magnet design. Subsequently, the contract was amended to increase the costs by 3 million deutsche marks (about $2 million). DESY officials pointed out that this cost increase did not increase the overall project cost because it was offset by cost reductions in other parts of the HERA project. Italy contributed the other half of the dipole magnets, which were industrially produced in Italy. DESY officials did not have cost information for these magnets.

After the contractors built a total of 30 preproduction magnets, which were tested at DESY, magnet production in both Germany and Italy began in mid-1989. DESY tested each magnet at room temperature (warm measurement) for mechanical and electrical measurements. Although DESY found that each magnet had mechanical measurement defects, most of the defects were corrected by the contractor at DESY. Less than 5 percent of the magnets had to be returned to the contractor for repair of the defects disclosed by DESY's warm measurements. DESY then cold tested each magnet at the operating temperature of -269 degrees centigrade for vacuum leaks and magnetic field quality. About 3 percent of the magnets failed the cold tests and were sent back to the contractor for repair.

The first magnets were installed in the ring in September 1989. To negate the effect of any slight variations that remained from having different contractors producing the magnets, the magnets from each contractor were placed in different octants of the ring. The first 52 dipole magnets were cooled down to operating temperature in March 1990. The contractors delivered the magnets according to schedule, and installation of the magnets was completed in September 1990. Half the ring was cooled down in

October 1990, and the other half of the ring was cooled down in December 1990. The first circulating proton beam is expected in the spring of 1991, and the first proton-electron collisions in HERA are expected in the autumn of 1991.

DESY'S COMMENTS ON INDUSTRIALLY PRODUCING MAGNETS

According to DESY officials, the key elements to their success in having industry produce superconducting magnets were

-- having one person at DESY with the authority and the knowledge needed for making all decisions concerning the technology, budget, and schedule for the magnets;

-- clearly identifying the specifications for the industrially produced magnets before going out for bids;

-- retaining the flexibility to negotiate with the contractor by maintaining ownership over the tooling and the technology; and

-- fully measuring and testing each magnet before accepting and installing it into the accelerator ring.

Centralized Authority for All Magnet Decisions

DESY gave one official the authority to make all decisions concerning the technology, budget, and schedule for the HERA magnets. DESY officials emphasized that this person had the technical knowledge needed and a fundamental understanding of the technical issues involved in developing and producing the magnets.

Because he had the necessary technical knowledge, the DESY official was able to make trade-offs between the competing demands of the project's technology, budget, and schedule. For example, such a trade-off was needed to resolve a problem involving persistent currents that distort the magnetic field of the superconducting magnets. The presence of these currents could prevent the accelerator from reaching the higher energy levels needed to carry out the desired physics experiments. DESY had to decide whether to make costly changes to the HERA magnets or take a riskier approach and keep within the budget. The DESY official decided to keep to the budget and modify the magnet design by adding correction coils to compensate for the effect of persistent currents. The persistent currents also change with time. The official told us that by continually measuring the strength of the persistent currents and adjusting the current in the correction coils, this problem should be solved. However, he will not know for certain until HERA's proton ring is operating (about April 1991).

The official informed us that he was willing to take this risk because he has a back-up approach in case the correction coils do not resolve the problem. With PETRA's existing magnets, the injection energy for the protons into HERA is 40 GeV. The magnets in the PETRA ring can be replaced with stronger conventional magnets that would produce an injection energy of 100 GeV. The higher injection energy should resolve the problem but would cost another 80 million to 100 million deutsche marks (about $53 million to $67 million) and delay the start-up of the experimental physics program.

In contrast to DESY, much of the expertise with superconducting magnets in the United States resides in Department of Energy (DOE) laboratories outside the Superconducting Super Collider (SSC) Laboratory in Texas. Fermilab and Brookhaven have had the lead roles in developing the superconducting magnets for the SSC. Lawrence Berkeley Laboratory in California has also been working closely with Fermilab on the magnets. In July 1990, DOE's High Energy Physics Advisory Panel (HEPAP) reported that SSC Laboratory did not have a "Mr. Magnet" to lead the magnet development and production effort.[5] In response to that report, according to the Associate Director of the laboratory's Magnet Division, the SSC Laboratory hired a senior person with expertise in superconducting magnets in October 1990. This person, who had worked with superconducting magnets at Lawrence Berkeley Laboratory, filled a senior staff position at the SSC Laboratory's Magnet Division.

DESY Clearly Identified Magnet Specifications

Before going out to industry for bids, DESY officials said they developed and tested prototype magnets and wrote detailed specifications for the superconducting magnets. They said that a proven technical design is needed before going out to industry. The DESY official responsible for the magnets added that it is critical not to underestimate the time needed to develop the magnets or to rush the preproduction.

DESY and a contractor, Asea-Brown-Boveri, worked together to successfully complete five prototype HERA magnets, which were carefully measured and tested. After considering all it had learned from the prototypes, DESY prepared detailed written specifications and went out for fixed-price bids. DESY officials said they assumed that if industry built to the laboratory's design, the magnets should work because the prototype magnets

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[5] Report of the 1990 HEPAP Subpanel on SSC Cost Estimate Oversight, U.S. Department of Energy, July 1990.

worked. Therefore, the laboratory held industry accountable for producing magnets that not only met specifications, but worked.

In contrast to DESY, the SSC Laboratory went out to industry for bids before building or testing a prototype magnet of the current design. In July 1990, the SSC Laboratory issued a request for proposal that did not include a detailed written design for the magnets. At that time, neither the SSC Laboratory nor any of the other DOE laboratories had built or tested a full-sized collider dipole magnet of the current design.

DESY Maintained Leverage Over the Contractor

DESY had flexibility to transfer the HERA magnet tooling and technology to other companies because it retained ownership of the tooling and technology, according to DESY officials. DESY wrote into the magnet development and production contracts that all tooling belonged to DESY and that DESY could give it to others. Even if the contractors developed or modified a technique, DESY had the right to use it for the production of HERA magnets at other manufacturers. This arrangement made credible DESY's ability to walk away from a contractor and thus have greater leverage in dealing with the contractor. In addition, two contractors were producing magnets. The official stated that both contractors were treated equally. If one contractor threatened to stop production, DESY could go to the other contractor for the magnets.

The SSC Laboratory is using a leader-follower approach to contracting for collider dipole magnet production. Under this approach, one contractor, the leader, will design and develop the tooling and techniques for producing the magnets. The SSC Laboratory will own the tooling and techniques, provide support to the leader, and conduct design reviews. Another contractor, the follower, will participate in reviews and meetings at which technical information is exchanged between the leader and the SSC Laboratory. Both the leader and the follower will produce 250 magnets as designed by the leader. The leader and the follower will then bid to produce the balance of the approximately 8,600 superconducting dipole magnets needed for the SSC. According to the July 1990 HEPAP report, the SSC Laboratory does not stay in control of the design. Further, the leader is not under competitive pressure to produce a good magnet design because the follower is constrained to follow the leader's design.

DESY Fully Measured and Tested Each Magnet

DESY officials stressed that each magnet needed to be fully measured and tested. DESY both warm measured and cold tested each magnet at DESY.

DESY had not originally planned to make warm measurements of each magnet but found such measuring was necessary because the first magnets produced by the contractors had many defects. Even after the contractors had done their quality control checks, most magnets delivered to DESY had mechanical inaccuracies, such as the holes on flanges that connect the magnets together not aligning. Most of the inaccuracies were minor and were easily corrected by DESY staff or, in more serious cases, by the contractor at DESY. Less than 5 percent of the magnets were sent back to the contractor because of the defects disclosed by DESY's measurement checks.

DESY officials said that cold testing of all the magnets by DESY was important because it gave them confidence that the magnets would work. DESY found it cost effective to do the final cold test of the magnets at the laboratory. The officials added that the final magnet test should be done by laboratory staff just before installation.

Although only about 3 percent of the magnets failed the cold tests, the tests disclosed defects that DESY's warm tests did not. The cold tests revealed small vacuum leaks difficult to detect at room temperature and problems in the magnet coils. About 10 magnets failed the cold vacuum test and 5 magnet coils did not meet the minimum required operating strength. The defective coils were discovered on magnets that were among the last to be produced. These magnets were returned to the contractors, who dismantled and repaired them.

In contrast to DESY, the SSC Laboratory plans to rely on the contractor for the warm tests and plans for itself to cold test a small sample of the magnets. The SSC Laboratory will cold test all of the first 10 percent of the magnets produced and then 10 percent of the remaining 90 percent before installing the magnets in the tunnel. After the magnets are installed in the tunnel, the SSC Laboratory plans to cold test each section of about 60 magnets. Once a magnet is installed, the SSC must identify and remove any defective magnets from the tested section.

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